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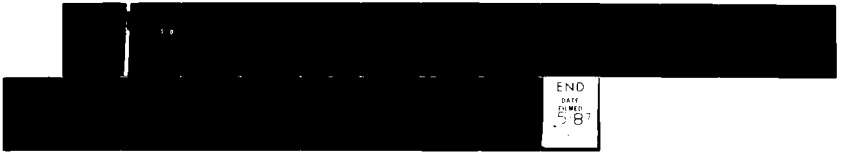

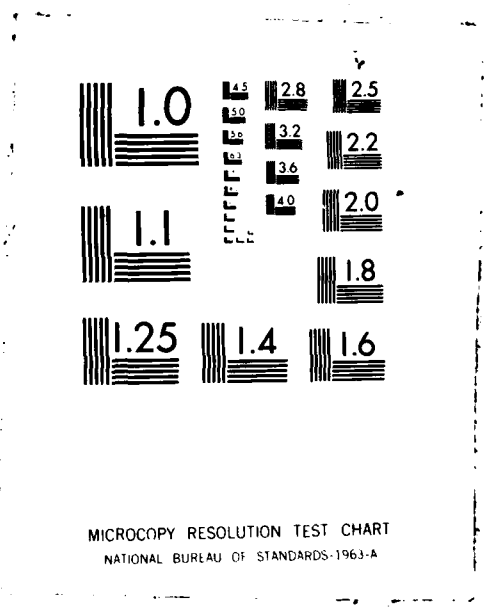
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MELBOURNE, VICTORIA

REPORT

MRL-R-1030

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A FAST, LOW RESISTANCE SWITCH FOR SMALL SLAPPER DETONATORS

D.D. Richardson and D.A. Jones

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A FAST, LOW RESISTANCE SWITCH FOR SMALL SLAPPER DETONATORS

1. INTRODUCTION

Slapper detonators designed to function at energies of less than a few joules require careful design. The electrical stripline connecting the detonator bridge to the firing capacitor and switch must have very low inductance [1] for efficient operation. Apart from this, the switch used to fire the detonator must have an extremely rapid closure time and low resistance relative to the slapper bridge itself [2]. This is required to ensure that the switch does not broaden the electrical firing pulse, and that it does not absorb a significant fraction of its energy.

The specifications for the switch are therefore stringent and limit the type of switch which can be used. To date, slapper switches have often been of the vacuum spark gap type [1], though these can have significant inductance, particularly without careful installation. Such switches are, however, expensive and difficult to make, requiring carefully out-gassed materials and accurate assembly.

The only effective alternative switch so far used has been a switch based on the concept of shock compression conduction (SCC), in which a shock wave from some detonating explosive is passed into a plastic insulator between the two electrodes of the switch. When the pressure is above a certain critical value, some plastics become electrically conducting [3,4,5]. This has proven to be a very effective switch for this application, though little attempt has so far been made to determine the optimum amount of explosive for reliable functioning [1,6]. In the United States, low energy EBW detonators, placed directly onto the stripline, have commonly been used to provide the shock wave. It has been found, however, that using an M100 detonator to provide the shock pulse gives more reliable switching of slapper detonators than using an RP87. The reason for this is assumed to be the concave dimple on the end of the M100 which probably shapes the output shock wave to some extent.

For this reason, and the suspicion that shock impedance matching will have a significant effect on the ultimate pressure in the insulating film, it was decided to consider using a switch in which an explosively driven flyer plate was made to impact the slapper detonator stripline. This would create the desired pressure in the insulator, rather than using the output of the explosive directly. Since the conductors on the stripline were made of copper film, (typically less than 25 μm thick), the flying plate was also made of copper, to permit maximum transfer of the shock wave energy into the stripline. A diagram of the arrangement used is shown in Figure 1.

The switch works as follows. A small quantity of lead azide is initiated from a hot wire*. The detonating azide initiates a column of RDX. The RDX detonation wave accelerates the copper plate across the gap onto the top conductor of the stripline. On impact a shock wave is generated at the interface, and propagates both into the top conductor, and back into the flyer plate. The pressure wave into the stripline will remain at a high value until pressure wave relaxation passes through the stripline from the rear surface of the flyer plate. This happens after the double transit time of the shock wave in the flyer plate. The magnitude of the pressure wave is determined by the plate impact velocity, which in turn is determined by the Gurney energy of the explosive [7].

Provided the pressure of the shock wave which passes from the top conductor into the Kapton insulation between conductors is above about 9 GPa [3], and the pressure pulse width is much greater than the shock transit time through the Kapton, current will rise very rapidly through the switch as the shock front reaches the bottom conductor, and will remain flowing for approximately the width of the shock pulse, less the time it takes for the shock front to pass through the insulator. The resistance of the switch will depend on the material of the insulator [4], and to a lesser extent on the magnitude of the shock pressure, provided the latter is above the critical conduction pressure.

The shock pulse produced by a flyer plate impact of this form has several desirable features. The shock front has a sharp and well-defined pressure increase, the pressure is almost constant for the duration of the pulse, and the duration of the pulse is accurately controlled by the thickness of the flyer plate. Also, because the flyer plate is made of the same material as the top conducting film, transfer of the shock pulse into the stripline is optimised.

The pressure wave from the detonation front itself, on the other hand, though it rises rapidly initially, reaches a maximum in a very short time (nanoseconds), and then decays exponentially in a manner which is characteristic of the explosive and its preparation (morphology, density, etc). This produces a pressure pulse in the stripline insulator, which though initially very high, is not very well defined or controllable without careful

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* A platinum EBW header was used. Later in this report we discuss the effects of replacing this header with a commercial "match head" initiator.

preparation of the explosive used. The closure and closed-state period of the switch, which both rely on the detonation wave characteristic of the explosive, may be quite variable.

This report presents calculations that were performed to produce a suitable design for a flying plate SCC switch. A simple Gurney model was used to predict terminal plate velocities for various tamper materials and thicknesses. The plate velocities thus calculated were used, along with geometric parameters to estimate the shock impedance behaviour of the stripline itself. Shock pressures and pulse durations were estimated in the top conductor and insulator. Using the fact that pressures must be above 9 GPa in the Kapton insulator for SCC to take place [3] and that a minimum electrical pulse duration of about 150 ns [1] is required for proper slapper detonator functioning, the geometric design parameters were varied to produce a range of near-optimal flying plate switch designs. Some limited experimental evidence that our new switch provides improved switching performance for the same quantity of explosive in the switch is also presented.

2. CALCULATIONS

The first step in the design process is to calculate the impact velocity of the flyer plate as a function of the tamper, explosive and flyer plate thicknesses. To do this we use the asymmetric flat plate Gurney expression [8], and ensure that the length of the airgap in the perspex case is at least equal to or slightly greater than the thickness of the RDX to allow sufficient distance for the flyer plate to be accelerated to the terminal Gurney velocity [7]. The one-dimensional asymmetric Gurney equation has the form

$$v_f = \sqrt{2E}\left\{\frac{1+A^3}{3(1+A)} + \beta A^2 + \alpha\right\}^{-1/2}, \qquad (1)$$

where $\alpha = M/C$, $\beta = N/C$ and

$$A = (1+2\alpha)/(1+2\beta).$$

Here M is the mass per unit area of the metal flyer plate while N is the mass per unit area of tamper material. $\sqrt{2E}$ is the characteristic Gurney velocity for the explosive used and C is the mass of explosive per unit area. In terms of the lengths and densities of tamper, explosive and flyer plate α and β are given by

$$\alpha = \frac{\rho_f t_f}{\rho_e t_e}, \quad \beta = \frac{\rho_t t_t}{\rho_e t_e} \tag{2}$$

where ρ_t, ρ_e and ρ_f are the densities of the tamper, explosive and flyer plate respectively and t_t, t_e and t_f their respective lengths.

Once the flyer plate impact velocity has been determined from the Gurney expression our next step is to estimate the pressure which this impact produces in the Kapton stripline. To do this we first ignore the presence of the thin (typically less than 25 μm) copper film on the surface of the Kapton. This approximation has little effect on the accuracy of the calculations as the flyer plate material is also copper and there are no impedance mismatch problems. This point will be discussed in more detail at a later stage. To calculate the pressure we use standard shock impact techniques [9]. The pressure in the stationary acceptor stripline is given by the momentum jump equation,

$$\begin{aligned} P_a &= \rho_a U_a u_a \\ &= \rho_a (C_a + S_a u_a) u_a \end{aligned} \tag{3}$$

where ρ_a is the density, u_a the particle velocity, and U_a the shock velocity in the acceptor material. It has also been assumed that the standard linear relationship between shock velocity and particle velocity is applicable, i.e.

$$U_a = C_a + S_a u_a \tag{4}$$

where C_a is the sound speed in the acceptor material and S_a is an experimentally determined parameter. Equation (4) defines the Hugoniot of the acceptor material. With similar assumptions for the flyer plate material the pressure pulse in the flyer is given by

$$P_f = \rho_f \{C_f + S_f (v_f - u_f)\} (v_f - u_f) \tag{5}$$

where u_f is the particle velocity in the flyer material and v_f the impact velocity of the flyer. The constants C_f and S_f for the flyer material have the same meaning as C_a and S_a for the acceptor. Equating pressure and particle velocity across the shock interface leads to the following equation for the common particle velocity u_I

$$\rho_a (C_a + S_a u_I)\, u_I =$$

$$\rho_f \{C_f + S_f (v_f - u_I)\}(v_f - u_I) \qquad (6)$$

with relevant physical solution

$$u_I = (-b + \sqrt{b^2 + 4ag})/2a \qquad (7)$$

where $a = \rho_a S_a - \rho_f S_f$,

$b = 2\rho_f S_f u_f + \rho_f C_f + \rho_a C_a$,

and $g = \rho_f u_f (C_f + S_f u_f)$.

Equation (7) can also be found in the paper by Kennedy and Schwarz [7]. The pressure in the Kapton stripline is then easily found from equation (3), with u_a replaced by u_I.

The final step in the calculation is to estimate the amount of time for which the switch will be closed. This depends on the thickness of both the Kapton stripline and the metal flyer plate. The switch will not close until the shock has reached the thin copper strip on the underside of the Kapton stripline, Figure 1, and it will then remain closed until the release wave from the free surface of the flyer plate relieves the pressure on the upper surface of the stripline. Hence the switch will be closed for a time equal to the double transit time of the shock in the flyer plate less the time taken for the shock to travel the thickness of the stripline insulator. The velocity of the shock in the flyer plate is given by $U_f = C_f + S_f (v_f - u_I)$, and so to a good approximation the double transit time is simply

$$\tau_f = 2 t_f / U_f. \qquad (8)$$

The time for the shock to travel a thickness t_a in the stripline is t_a/U_a, where U_a is given by equation (4), and so the time for which the switch is closed, τ_c, is given approximately by

$$\tau_c \simeq 2t_f/\{C_f + S_f(v_f - u_I)\} - t_a/(C_a + S_a u_I) \qquad (9)$$

The last point to be considered is the effect of the neglect of the thin copper film on the surface of the stripline. A simple calculation shows that the pressure transmitted into the Kapton through the copper film is the

same as would be produced by the impact of the flyer on the bare Kapton. This is true provided that the flyer plate material is the same as the material on the surface of the Kapton. There will be a slight delay in the operation of the switch due to the fact that the shock wave now has to travel through an additional layer of copper, but the switch closure time, as given by equation (9), will remain unaffected because the switch will not open again until the release wave from the back of the flyer plate has also passed through this additional thickness of copper.

3. RESULTS OF THE CALCULATIONS

The calculational scheme just outlined has been applied to two particular switch designs. The first has a Bakelite tamper 5.0 mm thick, an RDX layer 5.0 mm thick and a copper flyer plate 0.5 mm thick. The stripline consists of 30 μm thick Kapton with a 5 μm thick copper layer on either side. The effect of the lead azide was largely ignored in the calculation. The full length of explosive was assumed to comprise RDX. Since lead azide is a primary explosive, it has very low energy output, and as a result, it was thought a reasonable approximation to ignore its effect on acceleration of the copper disk.

Values for all relevant physical properties of each of these materials are listed in Table 1. Fig. 2 shows the calculated pressure in the stripline for a range of flyerplate thicknesses. As mentioned in the Introduction, the Kapton stripline will become conducting when subjected to a pressure greater than 9 GPa [3]. From Fig. 2 we see that this places an upper limit on the flyer plate thickness of 0.6 mm. From eqns. (8) and (9) the requirement that the switch be closed for at least 150 ns also places a lower limit on the flyer plate thickness. From Fig. 2 we see that this is approximately 0.33 mm. Hence there exists a very limited range of values for flyer plate thickness, and this is reduced even more when the Bakelite tamper (the header used) is removed. The switch closure time as a function of Kapton thickness is plotted in Fig. 3 for representative values of flyer plate thickness. These values apply either with or without the Bakelite tamper as the difference between the two cases is negligible on this scale.

The second switch design is similar, but with larger dimensions; a 10 mm Bakelite tamper, 10 mm RDX explosive and approximately 1.0 mm thick copper flyer. The stripline is again Kapton, 30 μm thick, with 5 μm thick copper films on either surface. As can be seen from Figs 4 and 5, the larger dimensions result in less stringent limits on the flyer plate thickness, as well as longer switch closure times.

4. EXPERIMENTAL RESULTS

The results presented above are in qualitative agreement with the experimental results available to date. Firings with the smaller quantity of RDX and a 0.4 mm thick flyer plate have shown good bridge burst characteristics and evidence of efficient switch operation, while firings with both the flyer plate and airgap removed, i.e. with the RDX in direct contact with the stripline, have shown incomplete bridge burst and evidence of higher switch resistance.

The experimental results were obtained with an SCC switch containing 30 mg of lead azide and 100 mg of RDX in a 4 mm diameter column. It was found that in some cases switching was not as good as in others, evidenced by non-firing of the slapper detonator, and by lack of or inadequate formation of a slapper flyer plate. It was inferred from this behaviour that the RDX was sometimes not detonating due to insufficient lead azide around the hot wire. The quantity of azide used was therefore increased to 90 mg, with the result that functioning of the SCC switch has become extremely reliable and repeatable in the slapper switching role. It was noted [11] that 50 mg of lead azide is considered necessary to give complete initiation of RDX, though the geometric configuration of the explosives can be important also.

For practical convenience we also investigated the feasibility of using an electric "match head" as the initiator, rather than a hot wire. Calculations with reduced tamping showed that we could expect slightly reduced performance of the switch with an estimated 10–15% reduction in impact pressure from the copper disk. Experiments with slapper detonators indicated no significant difference in switching performance with 0.4 mm flyer disks. This suggests that under the conditions considered, both forms of switch produce a copper flying plate which is travelling above the threshold velocity for proper switching.

In the absence of suitable high speed recording instruments to accurately monitor the resistance of the SCC switch as a function of time, it is still possible to obtain useful qualitative information on performance by using dent tests to monitor copper disk flyer plate velocity. The results of these tests are presented in Table 2. The dents were measured using a travelling microscope with a depth of field of less than 10 μm. The "bottom" of the dent was carefully scanned to locate the lowest point, while the reference point on the undamaged portion of the block was taken well away from the region of the dent (typically at least 5 mm away). Reference points on both sides of the dent were taken to ensure flatness of the dent block.

The dents obtained with the copper disks all had a diameter approximately the disk diameter of 4 mm. Most of these dents had smooth sides, and bottoms of varying roughness. The dents made with the explosive in contact with the block were much wider and rounded or dished, being 10 mm or more across, and not having a flat bottom.

Table 2 shows the following interesting results.

1. The use of extra lead azide produces much greater dents, and better reproducibility, probably as a result of the much higher probability of the RDX achieving detonation. The 90 mg of lead azide evidently produces a more reliable transfer of detonation to the RDX.

2. Replacement of the Bakelite-type header with a match head, thereby reducing any tamping effect, reduces the copper disk dent slightly, as our calculations predicted it should.

3. Dents from explosive in contact with the block (no disk, no gap) were generally lower than those from flying plates. This can be seen by comparing tests 8, 9 and 10 with tests 1, 7 and 12-15. The reason why test 7 has a much smaller dent than other equivalent tests is not known. It is possible that the copper disk was not in intimate contact with the explosive prior to detonation. Subjective visual inspection of the dent shape and size tends to support the depth measurements.

4. The 3.5 mm gap originally adopted for this switch should be increased for increased disk velocity. The terminal velocity of the disk is reached after about 8 mm (Test 13). If the gap is too long, the disk becomes unstable, as it appears to have done in shot 15. For the latter test, the dent was distorted in shape, being elongated and having a very uneven bottom. [Note that all gaps greater than 4 mm were produced with a spacing ring which had an internal diameter of 5.5 mm, i.e. larger than the diameter of the disk or the perspex case.]

The dent tests therefore confirm our model predictions, and complement our observations on the performance of the switch with actual slapper detonators.

5. CONCLUSIONS

We have presented a novel design for a shock compression conduction switch for use with slapper detonators. The design model uses simple Gurney analysis and basic shock wave theory. The effects of tamper, flyer plate thickness and donor explosive thickness on impact pressure in the slapper stripline were analysed. This enabled us to define a limited range of suitable flyer plate thicknesses which would provide the required pressure of 9 GPa in the stripline insulation for a period of not less than 150 ns. Estimates of the effect of the thickness of the stripline insulation on the time for which the switch remains closed are given for a range of flyer plate thicknesses and for two donor explosive thicknesses. The effect of flyer plate thickness on closure time of the switch was noted.

The new switch has been tested both by using it to function slapper detonators themselves, and by performing dent tests on aluminium blocks. Significant improvements in performance of the switch over that for a like amount of explosive initiated against the stripline were found, both in slapper detonator function and in the depth of dent measured.

The dent tests also revealed that the optimum gap length is around 8–10 mm for a 5 mm column of RDX. This implies that the gap should, in fact, be greater than the donor length, and probably about 1.5 to 2 times the latter, for the current switch design.

The dent tests also showed some effect of altering the degree of tamping – removing the tamping from a Bakelite header produced dents which were significantly smaller.

It may therefore be concluded that as a result of improved impedance matching our new SCC design gives greater switching efficiency than former SCC switch types. Apart from providing a very rapid pressure rise on impact, the flying copper disk in our design shapes the pressure pulse into the stripline insulation, giving reliable and reproducible performance.

6. ACKNOWLEDGEMENTS

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TABLE 1

Tamper Parameters

Material: Bakelite

Density: 1414 kg/m^3 [assumed similar to Kapton]

Explosive Parameters

Material: RDX

Density: 1590 kg/m^3 [7]

Gurney velocity, $\sqrt{2E}$ = 2.45 $mm/\mu s$ [10]

Flyer Plate Parameters

Material: Copper

Density: 8930 kg/m^3 [7]

Hugoniot parameters, C = 4.0 $mm/\mu s$ [7]
S = 1.50

Stripline Parameters

Material: Kapton

Density: 1414 kg/m^3 [12]

Hugoniot parameters, C = 0.93 $mm/\mu s$ [12]
S = 1.64

TABLE 2

Dent Tests 4 mm diameter column in perspex (plexiglass)

Test No.	Flyer plate (0.4 mm)	Stand off (mm)	RDX (mg)	Lead Azide (mg)	Header Type	Dent (mm)
1	Cu	3.5	100	90	Pt wire	1.6
2	Cu	3.5	100	30	Pt wire	.09
3	Cu	3.5	100	30	Pt wire	1.25
4	Cu	3.5	100	30	Pt wire	0.16
5	none	0.0	100	30	Pt wire	0.14
6	Cu	15.0	100	30	Pt wire	0.7
7	Cu	3.5	100	90	Match head	0.94
8	none	0.0	100	90	Match head	1.15
9	none	0.0	100	90	Match head	1.1
10	none	0.0	100	90	Match head	1.0
11	Karinga case used - not relevant to this series					
12	Cu	4.0	100	90	Match head	1.41
13	Cu	8.0	100	90	Match head	1.43
14	Cu	11.5	100	90	Match head	1.53
15	Cu	14.0	100	90	Match head	1.54

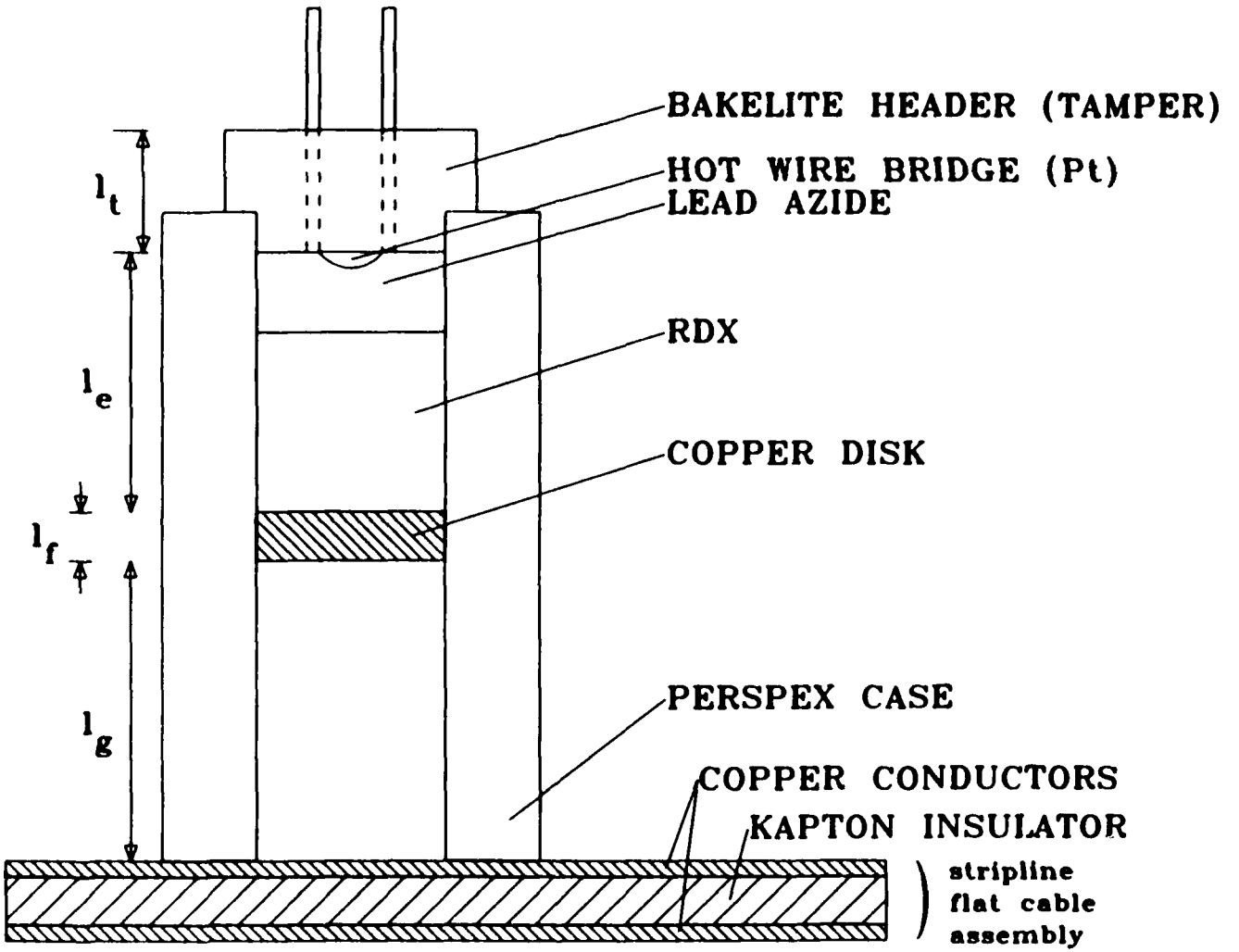

FIGURE 1 Diagram showing the MRL SCC flying plate switch for slapper detonators.

Explosive: 5mm RDX
Tamper : 5mm Bakelite
Copper flyer

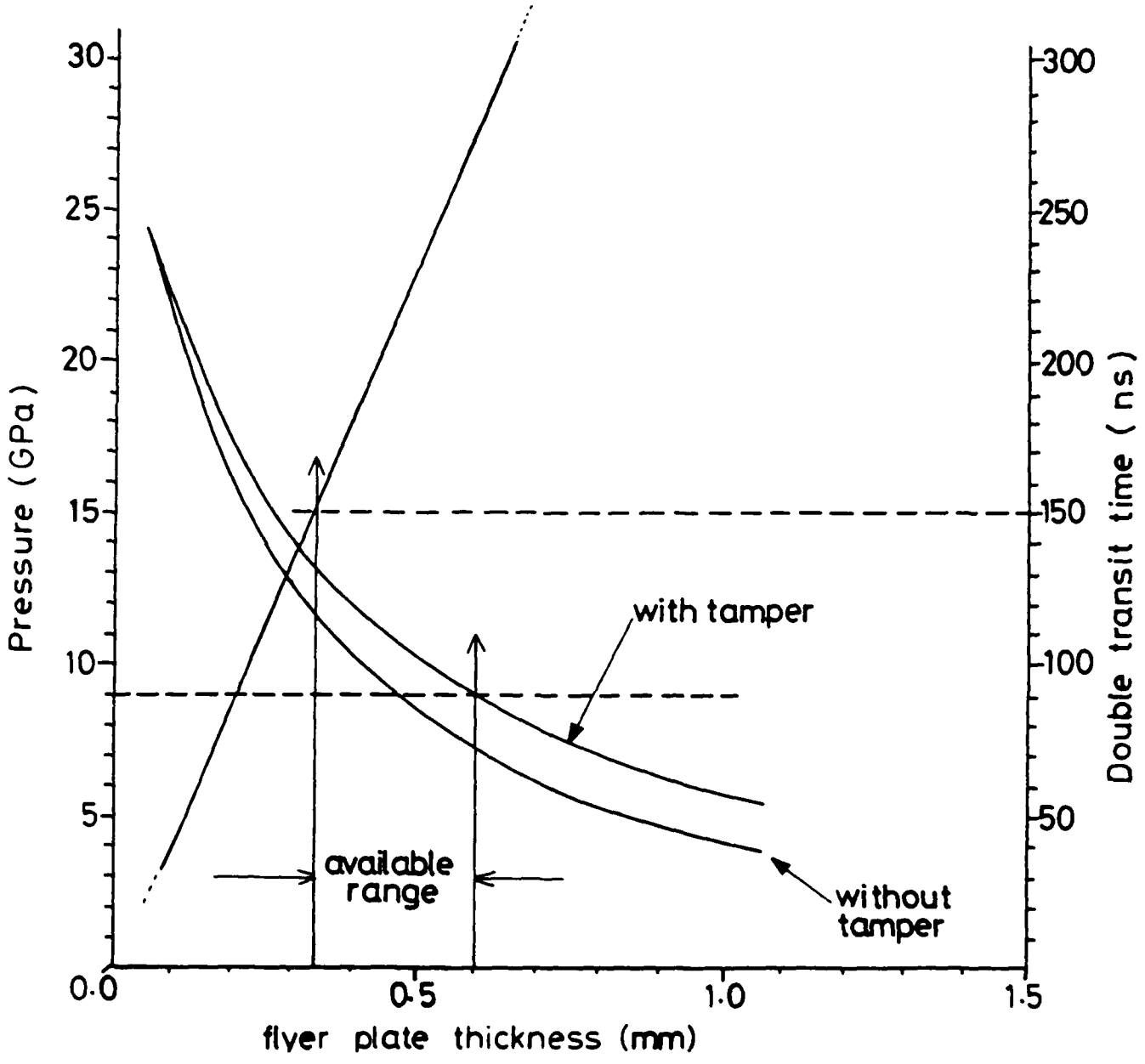

FIGURE 2. Graph showing pressure in Kapton stripline as a function of flyer plate thickness, both with and without tamper, for the small charge. Also shown is the double transit time within the flyer plate as a function of flyer plate thickness. This diagram shows the limited range available for flyer plate thickness when the constraints of a pressure greater than 9 GPa and a double transit time greater than 150 ns are taken into consideration.

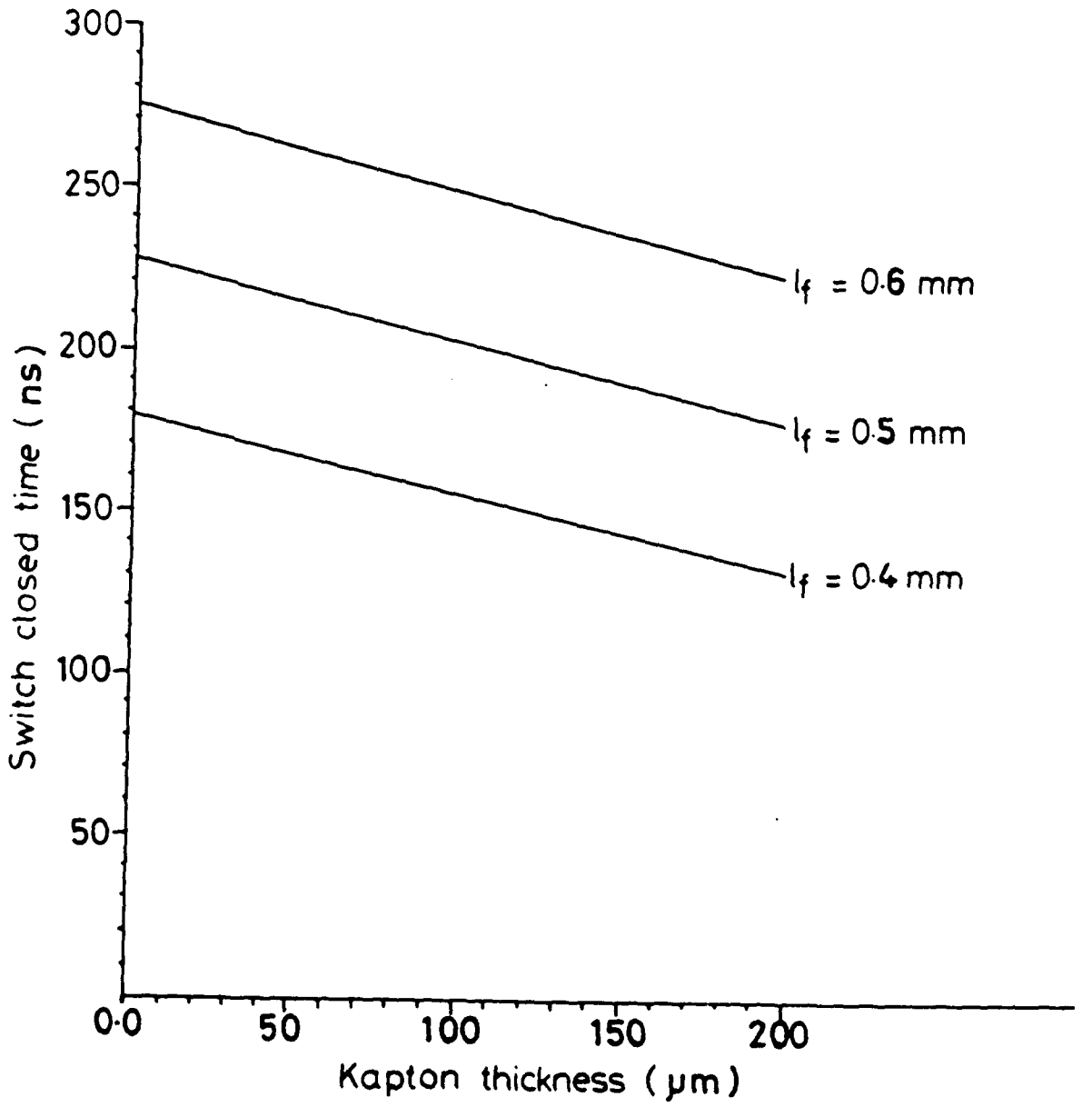

FIGURE 3. This graph is for the smaller charge and shows the total time for which the switch is closed as a function of the Kapton stripline thickness. The different curves are for different values of flyer plate thickness.

LARGE CHARGE

Explosive : 10mm RDX

Tamper : 10mm Bakelite

Copper flyer

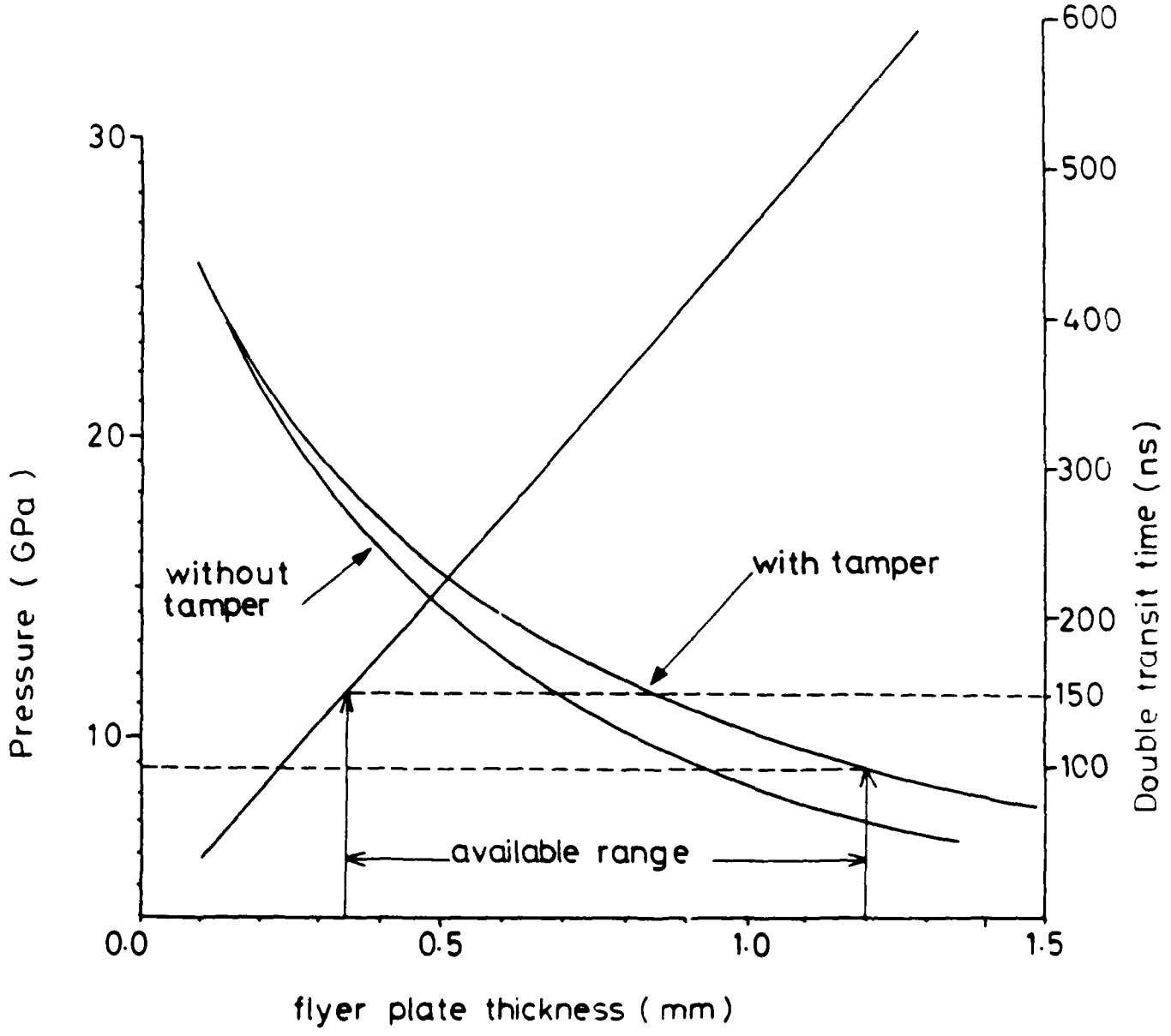

FIGURE 4. Same as Figure 2, only for larger charge.

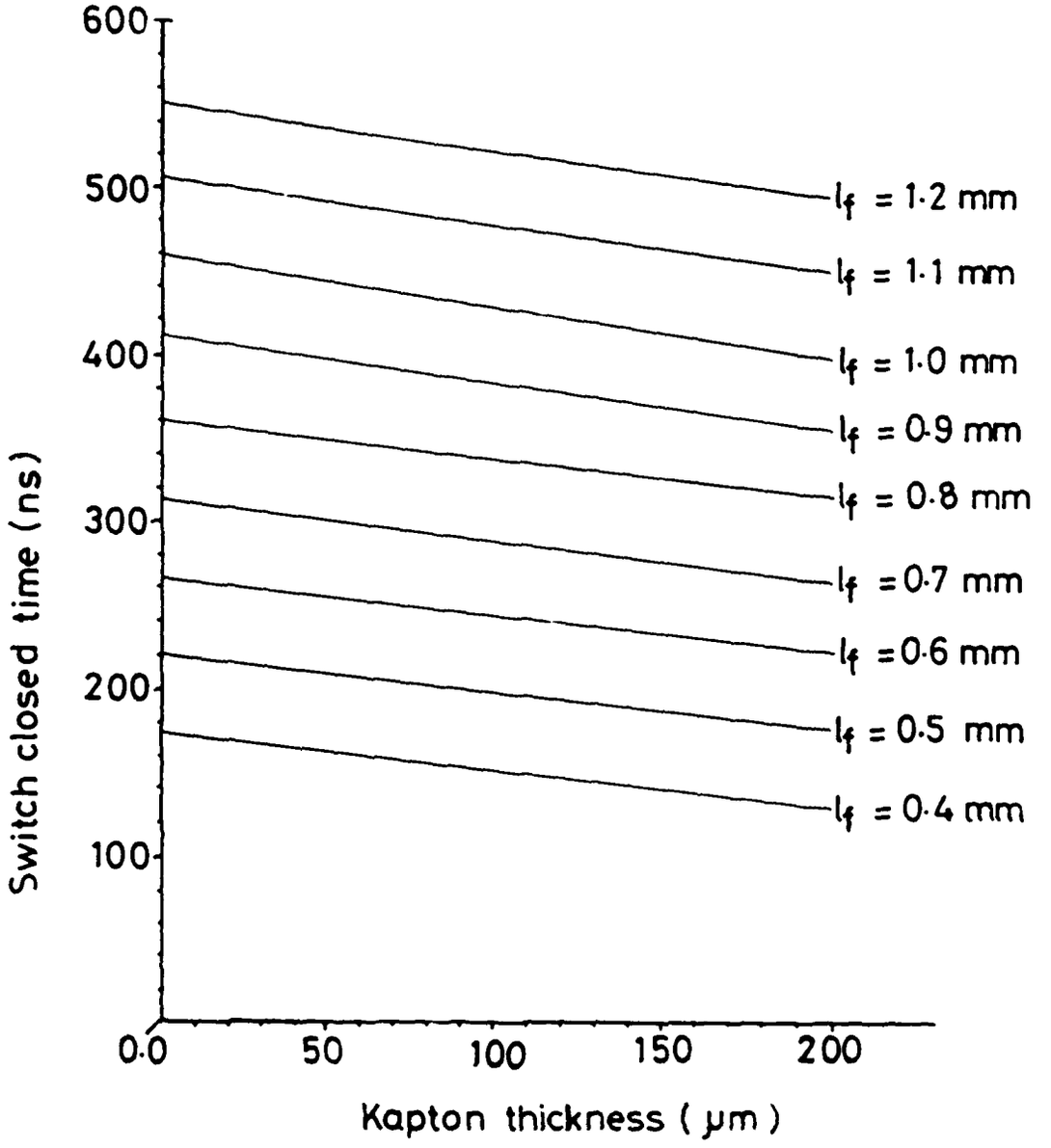

FIGURE 5. Same as Figure 3, only for larger charge.

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